VISION SENSING FOR CONTROL OF LONG-REACH FLEXIBLE MANIPULATORS

Klaus Obergfell, Wayne J. Book
The George W. Woodruff School of Mechanical Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332-0405, USA
www:http://davinci.marc.gatech.edu

Abstract

This paper presents an end-point position measurement method for long-reach flexible manipulators using a landmark tracking system (LTS). The LTS is based on a computer vision system designed for the tracking of retroreflective landmarks. Hardware and software components of the LTS are described and the calibration procedure and sensing performance are discussed. Two methods are suggested to improve the performance of the current system.

Keywords

Position Sensing, Computer Vision, Landmark Tracking, Flexible Manipulator, End-Point Position

Introduction

Flexible Manipulators

The rigid structure and large mass which characterize current industrial manipulators simplify motion control but limit speed, payload, and workspace. The flexible manipulator, an approach to overcome these limitations, has received much attention in the scientific community during the last decade, Book (1993). When the rigid structure design concept is abandoned, speed, payload, and energy efficiency can be increased using light-weight designs. However, compensation for deflection and vibrations has to be provided through control. Flexible beams are distributed parameter systems and, in theory, have an infinite number of degrees-of-freedom. For control purposes the dynamics are typically truncated to a finite number of flexible modes, e.g. using the assumed modes method. To sense these modes the sampling frequency has to be at least twice the frequency of the highest mode of interest according to the sampling theorem. Further, the position resolution needs to be high enough to detect the small vibration amplitudes of higher modes.

End-Point Position Sensing

End-point position sensing and control are important for accurate task performance with flexible manipulators. Because of the structural flexibility, it is not feasible to estimate the end-effector location from joint positions using a kinematic relation, which is typically done with industrial robots. Since most manipulators are already equipped with joint sensors, the end-point position of a flexible manipulator could be estimated by adding additional sensors measuring link deflections. However, unmonitored compliance, e.g. base deformation, makes this indirect measurement less accurate than a direct measurement. A direct end-point position sensor can be mounted on the manipulator itself or be placed in the environment. When the sensor is mounted on the manipulator the distance between a goal and the tip of the manipulator can be measured directly and the whole workspace can be observed. However, the problem of a moving measurement coordinate system has to be addressed. This is avoided when the sensor is mounted in the environment, but in this case, the sensor range may be limited because of accuracy constraints and obstacles. Observation of the whole workspace might, therefore, require several sensors.

Previous Work

Lateral-effect photodiodes have been used for measurements of end-point position and link deflection of flexible manipulators by Cannon and Schmitz (1984), Wang et al. (1989), Yim (1989), Obergfell and Book (1994). These sensors provide high resolution and high sampling frequency, but are limited to a relatively small field of view. These characteristics make them best suited for link deflection sensors.

CCD-TV cameras have been used for a variety of measurement applications for flexible manipulators by, among others, Oakley and Cannon (1990), Tang et al. (1990), and Morikawa et al. (1991). Landmark tracking systems as described by Nam and Dickerson (1991), and Obergfell and Book (1992) are also based on CCD technology but can sample faster than cameras built for TV applications. This paper is an extension of previous work by Obergfell and Book (1992) which improves sampling rate and workspace by using commercial equipment. This facilitates dynamic end-point position measurements of a long-reach flexible manipulator.

Flexible Manipulator Testbed

The vision sensor is implemented on a large flexible manipulator testbed denoted RALF (Robotic Arm, Large and Flexible) at the Intelligent Machines and Dynamics Laboratory (IMDL) at Georgia Tech. The manipulator operates in the vertical plane and consists of two 3 m long flexible links and a parallel link mechanism for actuation of the second joint. Both joints are hydraulically actuated. Length and velocity of the hydraulic cylinders are measured using colocated linear displacement transducers from which joint angles are computed in software. Deflections of the individual links can be monitored using lateral-effect photodiodes.

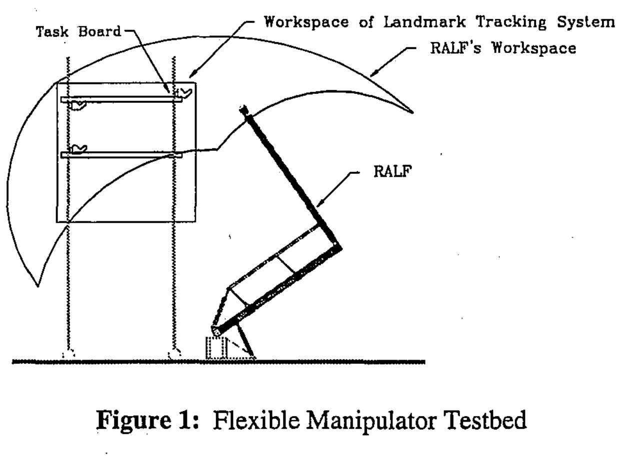

Figure 1: Flexible Manipulator Testbed

Landmark Tracking System

The landmark tracking system (LTS) consists of a low-cost, integrated vision system (IVS), retroreflective landmarks, software, illumination, and optics. The optical axis of the IVS is perpendicular to the plane of motion and a landmark attached to the manipulator tip can be tracked in a subspace of the manipulator's workspace as illustrated in Figure 1.

Integrated Vision System

The IVS used is a Stinger 70 by Dickerson Vision Technologies, Inc., which combines image capturing and processing in one functional unit. It consists of a lens assembly containing a CCD array sensor of 200 by 165 pixels, an 8-bit analog-to-digital converter, a 68000 microprocessor, a 68901 multi-function peripheral device, and memory. All operations of the IVS are controlled by the 68000. The 68901 is utilized for timing the image capturing process and for communicating with an external host computer through an RS-232 serial line.

Landmarks and Landmark Tracking Software

Retroreflective landmarks are used with the IVS to yield precise position measurements quickly. When properly illuminated the light reflected by a retroreflective landmark is very bright. This is exploited by the landmark tracking software which searches a mostly dark image for a bright spot. A bright light source could be mistaken for a landmark, but size and shape can be used to distinguish a landmark. Round retroreflective landmarks are used for this application, since they provide a good position resolution in all directions.

The landmark size influences resolution, detectability and processing time. A large landmark yields better resolution since more pixels are averaged but it takes longer to process. A small landmark is processed quicker but resolution degrades and it is harder to detect and could be mistaken for noise. A compromise between those extremes is sought and a landmark yielding an area of 12 pixels is used.

The landmark tracking algorithm searches the image for a bright spot, grows the spot, checks the condition for a landmark, and computes the center of gravity.

The search routine *row-scan* compares pixel intensities to an upper threshold value. If the pixel intensity exceeds the threshold a candidate for a landmark has been found, *row-scan* is suspended and the region growing routine *blob-growing* is invoked. As the name implies, the image is searched by rows. Initially when the landmark position is unknown *row-scan* starts at the center row of the image. Once a landmark has been acquired the search starts at the row of the previous landmark location. The search then continues with the row above the starting row, followed by the row below the starting row. This alternating search pattern is repeated until the landmark is found or the whole image has been searched.

Blob-growing checks if the four direct neighbors of a pixel should be included in the region. Again, pixel intensities are compared to a threshold, using a lower threshold for region growing. The upper threshold is set high to filter out noise and it is typically triggered by the brightest pixels in the middle of the landmark, while the second threshold is significantly lower to include the remaining pixels. *Blob-growing* starts with the neighbors of the initial pixel. If they pass the inclusion test their index and intensity are pushed onto a stack to be processed later and their image intensity is set to zero to avoid repeated processing. This process is then repeated with the pixel data previously pushed onto the stack until the stack is exhausted.

To test if a valid landmark has been found we compare the area of the region found to an upper and lower bound. This simple test is sufficient with our current setup. Additional tests could be run if necessary to include shape comparisons based on second or higher moment of inertia. If these tests are passed we have found a valid landmark and the center of gravity is computed using the data collected by *blob-growing*. The landmark tracking algorithm completes with sending the landmark position to the host computer and either waits for a new request or processes the next image.

Illumination

Illumination serves two purposes: To illuminate the retroreflective landmark material, and to freeze motion. The short-arc Xenon strobe used fulfills those requirements and matches the spectrum of the CCD in the IVS. The IVS does not use a shutter and therefore charges build up on the CCD during image exposure (wanted) and continue to build up while the image is shifted out for data acquisition (unwanted). This would result in a smeared image of a moving landmark, if continuous illumination would be used. To freezes the motion we use strobe illumination which applies a burst of light during image exposure while the amount of light received by the CCD during data acquisition is comparatively small. To yield a bright image of the retroreflective landmarks the strobe is mounted with its optical axis almost coaxial with the IVS.

Optics and Vision System Placement

The IVS is mounted stationary on the laboratory wall with a line of sight perpendicular to the manipulator's plane of motion. The distance between this plane and the IVS is 5.7 m. To maximize the field of view a telephoto lens is used which results in an observable area of 2.7 x 2.7 m within the manipulator's workspace (Figure 1). The retroreflective landmark is attached to the tip of the manipulator.

Sensing Performance

Calibration

The following calibration procedure was used to align the LTS such that the image-plane is parallel to the manipulator's plane of motion and to convert pixel measurements to end-point position measurements. We constructed a rectangular template with landmarks at the four corners and attached it to the taskboard (Figure 1). The alignment of the LTS was then modified until the landmarks in the image of the template were oriented correctly. The conversion factor from pixels to length was then computed using the known distance between the template landmarks. This yields a relative end-point position measurement.

To get an absolute end-point position measurement we measured the location of the calibration template relative to the manipulator base. Without a theodolite this is difficult because of the large dimensions involved. We used tape measure for distance measurements, plumb-bob to check vertical alignment, and right angle to check orthogonality. Using these tools the calibration is very time consuming and its accuracy is limited

A second set of measurements was performed to verify and correct the first calibration. We used a level that had two landmarks attached to it, a known distance apart. The level was placed horizontally and vertically in the manipulator's plane of motion. Position measurements based on the first calibration were then compared to manual measurements of the level position with respect to the manipulator base and the calibration was corrected accordingly.

Repeatability

In general, the repeatability of the landmark tracking system is influenced by calibration accuracy, landmark size and shape, illumination consistency, optical distortion, software and hardware discretization, and computational resolution.

The computational resolution of the LTS is 1/256 of a pixel because the IVS doesn't provide floating point hardware and one byte is dedicated by software to the remainder of fixed point computations. We determined repeatability experimentally since the other factors above are difficult to quantify. Figure 2 and Figure 3 show the variation of a fixed landmarks position in pixels over a 10 second interval (200 samples). Both Figures show a variation of less than 0.03 pixels or 3 bits, which corresponds to position variations of less than 0.4 mm in the vertical direction and 0.5 mm in the horizontal direction.

The measured pixel noise can be explained by structural vibrations in addition to the above factors.

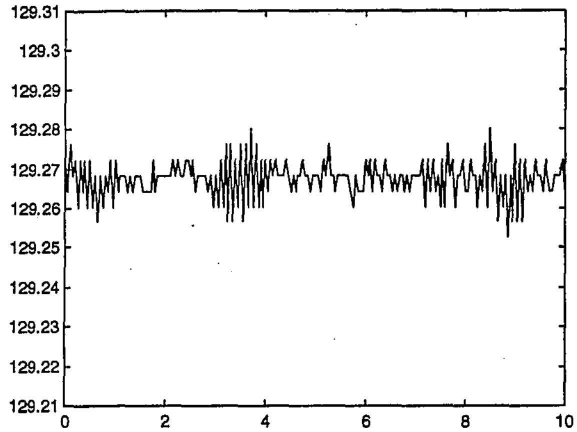

Figure 2: Pixel noise of the landmark tracking system in horizontal direction

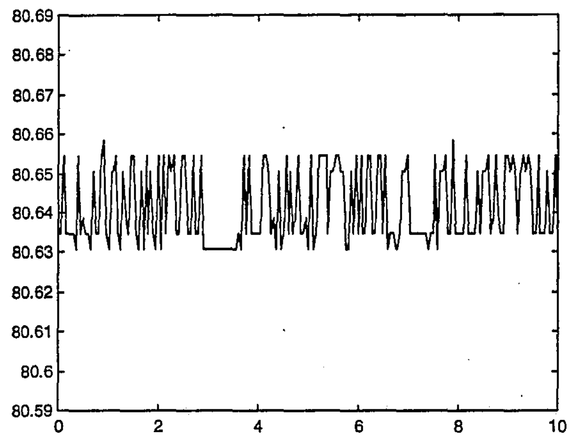

Figure 3: Pixel-noise of the landmark tracking system in vertical direction

Accuracy and Comparison with other Sensors

Two accuracy measures were obtained through the calibration process: Relative position measurement accuracy, position between two landmarks, and absolute position measurement accuracy, position with respect to the manipulator base. The relative accuracy is approximately 1.5 mm, which was obtained by comparing the known distance between the landmarks on the level with the distance between the measured landmark positions. Relative accuracy matches well with repeatability, since it is composed of two times the repeatability, once per landmark, plus the measurement uncertainty to determine the distance between the landmarks on the level. The absolute accuracy is approximately 10 mm, due to the measurement uncertainty relating the base of the manipulator to the calibration template. However, for practical purposes the relative positioning accuracy is more important and the achieved accuracy would be adequate for a long-reach manipulator.

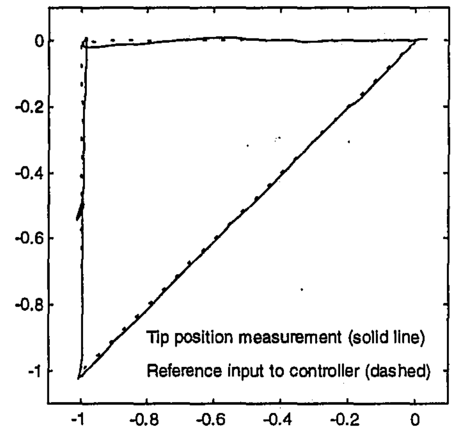

Figure 4: Tip position measurement using landmark tracking system

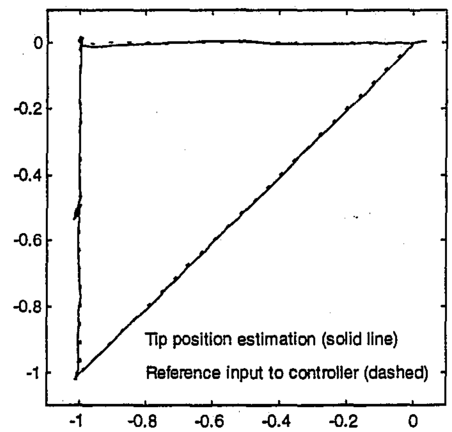

Figure 5: Tip position estimation using manipulator based sensors

The tracking accuracy of the LTS was also compared to an estimation of the tip position using joint angle sensors and link deflection sensors. A previous static experiment, Obergfell and Book (1994), had shown good correspondence between dial indicator measurements and LTS measurements during payload variation, while the estimate had shown less compliance. This was found to be due to compliance not monitored by the manipulator based sensors. Figure 4 displays the tip position measurement using the LTS when the manipulator is commanded to follow a triangular tip trajectory. Note that the tip position measurement is not used for feedback control purposes. The reference input shown corresponds to the fictitious end-point position of a rigid robot. Figure 5 shows the corresponding plot using the estimation from joint angle and link deflection sensor readings. Both plots show qualitatively very similar results, however, the LTS measurement displays more compliance than the estimate. This confirms the result of the previous experiment

Sampling Rate

The CPU of the IVS controls all processes of the LTS. On the Stinger 70 used these are implemented sequentially. The sampling rate of the LTS can therefore be estimated by adding the individual process times given in Table 1. The duration of the search algorithm was estimated by comparing the times of entire image scans and direct hit scans. The timing of the region growing algorithm is estimated from tests with different size landmarks. The calculation and overhead time was introduced to match total sampling time calculations to experimental data, this correction is less than 5 % of the minimum sampling time.

Process	Process Time in ms
Communication with host	3.12 (12 byte, 38400 Baud)
Exposure	0.5
Data acquisition	6.714
Searching	0.014 per pixel (*)
Region growing	2.76 (*) (12 pixels per landmark, 0.23 per pixel)
Calculation, overhead	< 1 (*)

Table 1: Process times of the landmark tracking system (* Estimate)

Table 2 gives sampling times for best, worst, and typical operation of the LTS. The typical sampling time assumes that 3 rows have to be scanned to find the landmark. At this sampling rate the manipulator tip can be tracked at tip speeds of up to 2.5 m/s. The tip speed of RALF is usually below 1 m/s. Assuming that frequencies of up to one forth of the sampling frequency can be identified, it would be possible to track the first two modes of RALF using the LTS. The first natural modes of RALF are approximately 6, 12, 38, 57 Hz, according to Huggins et al. (1987). Significant improvements would have to be made to identify the third mode with the LTS, since the third mode is faster than the minimum sampling time. Aliasing of the higher modes would theoretically distort the measurements of the LTS, since it is a digital sensor. However, the amplitudes of the higher modes are very small, so that aliasing has an insignificant effect on the measurement. The small amplitudes also reduces the importance of the higher modes for control purposes.

	Minimum Time	Maximum Time	Typical Time
Search Time in ms	0.014 direct hit	113.4 entire image	4.2 3 rows
Sampling Time in ms	14.1	127.49	18.29
Sampling Frequency	70.9 Hz	7.8 Hz	54.7 Hz

Table 2: Sampling time and frequency of the landmark tracking system

Conclusion

A landmark tracking system based position sensor with fast sampling rate and good position resolution was presented. With this sensor we are able to identify the first two natural modes of the studied long-reach manipulator, since the sampling frequency is more than four times the second natural frequency and the position resolution is 0.1 to 0.05 times the vibration amplitude. However, the calibration for absolute position measurements is difficult and the workspace is limited. Two suggestions are made for improvements. First, if the current workspace is sufficient, it would be advantageous to use relative position measurements, placing additional landmarks at target locations. This simplifies the calibration since image based measurements could replace the transformation to absolute measurements and it is also practical since the target location is not necessarily known in absolute coordinates. Second, if the workspace has to be increased, the sensing method could be improved by placing the LTS at the tip, measuring relative distance to a target as described above and using link deflection sensors to compute the orientation of the LTS with respect to the actuators and to improve the sampling rate of the overall system through sensor fusion.

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References

Book, W. J. (1993) "Controlled Motion in an Elastic World", *ASME Journal of Dynamic Systems, Measurement, and Control*, Vol. 115, No. 2(B), June 1993, pp. 252-261.

Cannon, R. H., Jr. and Schmitz, E. (1984) "Initial Experiments on the End-Point Control of a Flexible One-Link Robot", *The International Journal of Robotics Research*, Vol. 3, No. 3, Fall 1984, pp. 62-75.

Huggins, J. D., Kwon, D.-S., Lee, J. W., and Book, W. J. (1987) "Alternative Modeling and Verification Techniques for a Large Flexible Arm", *Proceedings of the Conference on Applied Motion Control*, Minneapolis, Minnesota, USA, June 16-18, 1987, pp. 157-164.

Morikawa, H., Takanashi, N., and Tagawa, N. (1991) "A Telerobot System for Space Antenna Assembly Experiments", *Proceedings of the IEEE International Workshop on Intelligent Robots and Systems*, Osaka, Japan, November 03-05, 1991.

Nam, Y. and Dickerson, S. L. (1991) "Position Estimation with Accelerometer and Vision Measurement", *Advances in Instrumentation*, DSC-Vol.30, ASME Winter Annual Meeting, Atlanta, Georgia, USA, December 01-06, 1991, pp. 1-8.

Oakley, C. M. and Cannon, R. H. (1990) "Anatomy of an Experimental Two-Link Flexible Manipulator Under End-Point Control", *Proceedings of the IEEE Conference on Decision and Control*, Vol. 2, Honolulu, Hawaii, USA, December 5-7, 1990, pp. 507-513.

Obergfell, K. and Book, W. J. (1992) "End-Point Control of a Two-Link Flexible Manipulator Using the Landmark Tracking System", *Proceedings of the Japan/USA Symposium on Flexible Automation*, Vol. 1, San Francisco, California, USA, July 13-15, 1992, pp. 701-706.

Obergfell, K. and Book, W. J. (1994) "End-Point Measurements of Long-Reach Flexible Manipulators", *Symposium on Robot Control '94*, Vol. 2, Capri, Italy, September 19-21, 1994, pp. 669-674.

Tang, P. C., Wang, H. C., and Lu, S. S. (1990) "A Vision-Based Position Control System for a One-Link Flexible Arm", *Intelligent Motion Control. Proceedings of the IEEE International Workshop.*, Vol. 2, Istanbul, Turkey, August 20-22, 1990, pp. 523-528.

Wang, W.-J., Shui-Shong, L., and Hsu, C.-F. (1989) "Experiments on the Position Control of a One-Link Flexible Arm", *IEEE Transactions on Robotics and Automation*, Vol. 5, No. 3, June 1989, pp. 373-377.

Yim, W. (1989) "End-Point Deflection and Slope Measurement of a Flexible Robot Arm", *Proceedings of the SPIE, Vol. 1167, Precision Engineering and Optomechanics*, San Diego, CA, USA, August 10-11, 1989, pp. 194-203.